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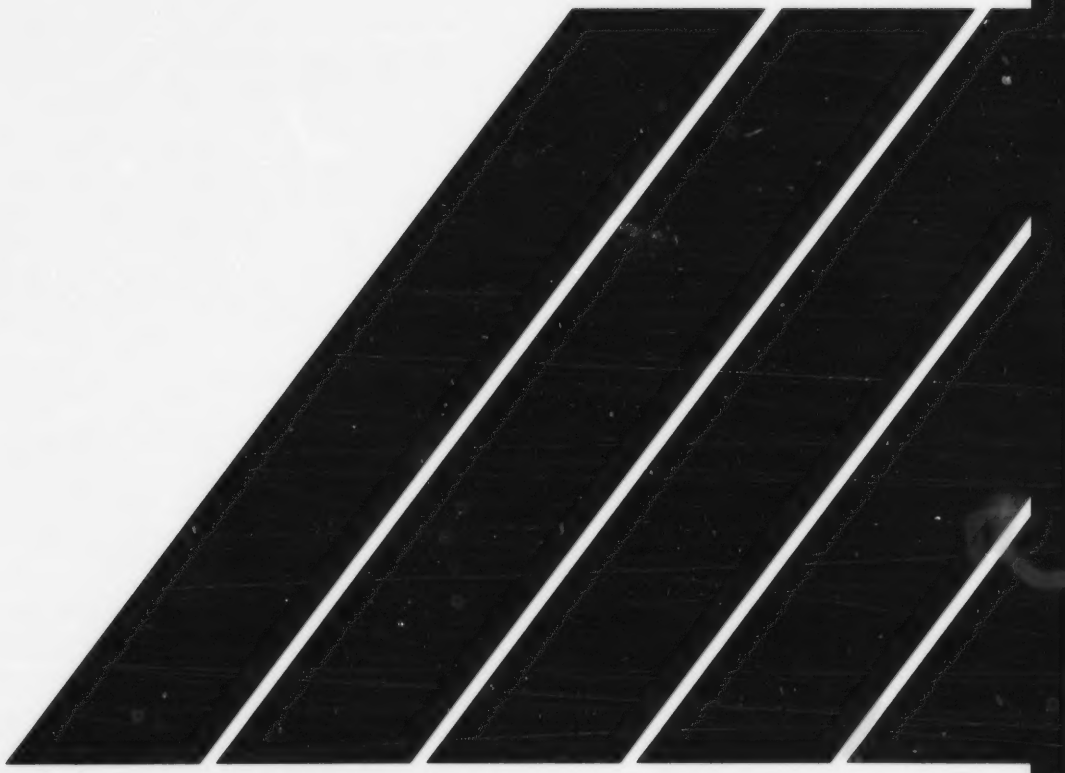

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LABORATORY AND FIELD EVALUATION OF ORGANIC CORROSION INHIBITORS IN SOUR MEDIA

V.S. SASTRI, P.R. ROBERGE AND V. MAXWELL

MTL 91-44(TR)

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LABORATORY AND FIELD EVALUATION OF ORGANIC CORROSION INHIBITORS IN SOUR MEDIA

by

V.S. Sastri, P.R. Roberge* and V. Maxwell*

ABSTRACT

Laboratory evaluation of the two organic inhibitors, 9662 and 9670, by AC impedance measurements showed the two inhibitors to be equally effective in the inhibition of corrosion. Microscopically measured pit depths on the samples correlated well with the sum of depression angles.

The polarization resistance data obtained from AC impedance measurements in the field showed both 9662 and 9670 to be effective inhibitors, with 9662 showing marginally superior performance to 9670.

The depression angle correlated fairly well with microscopically measured pit depths on the electrodes. The extent of pitting on samples exposed to inhibitor 9670 was slightly higher than samples exposed to inhibitor 9662. Detailed pit depth analysis by contracer and laser beam techniques leads to the conclusion that inhibitor 9662 is slightly superior to 9670 in inhibition of the degree of pitting.

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LABORATOIRES DE LA TECHNOLOGIE DES MÉTAUX
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ÉVALUATION EN LABORATOIRE ET SUR LE TERRAIN D'INHIBITEURS DE CORROSION ORGANIQUES DANS DES MILIEUX ACIDES

par

V.S. Sastri, P.R. Roberge* et V. Maxwell*

RÉSUMÉ

L'évaluation en laboratoire de deux inhibiteurs organiques, 9662 et 9670, par la methode de mesure AC-impédance, one montré que les deux inhibiteurs sont également efficaces pour inhiber la corrosion. Les profondeurs des piqûres mesurées au microscope sur les échantillons présentent une bonne corrélation avec la somme des angles de dépression.

Les données sur la résistance à la polarisation obtenues par des mesures de AC-impédance sur le terrain indiquent que les deux inhibiteurs 9662 et 9670 sont efficaces, mais que 9662 donne un rendement légèrement supérieur à 9670.

L'angle de dépression présente une assez bonne correspondance avec les profondeurs des piqûres mesurées au microscope sur les électrodes. La formation des piqûres est légèrement importante sur les échantillons exposés à l'inhibiteur 9670 que sur aux exposés à l'inhibiteur 9662. L'analyse détaillé de la profondeur des piqûres par traceur de contact et par faisceau laser amène à conclure que l'inhibiteur 9662 est légèrement supérieur à 9670 pour inhiber la formation de piqûres.

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INTRODUCTION

Both general corrosion and localized corrosion are encountered in sour gas gathering systems. Localized corrosion in the form of pitting corrosion is a serious problem in sour gas media because pitting corrosion failure is unpredictable, expensive and hazardous. In the case of localized corrosion, the rate of dissolution at local sites is much greater than that associated with uniform corrosion, and failure may occur in a short time. Addition of suitable inhibitors to control both the localized corrosion and uniform corrosion is a common practice in sour gas systems.

Monitoring the effectiveness of inhibitors in corrosion control in sour gas systems is an important aspect. Pipeline failures in the Grizzly Valley sour gas gathering system (1), corrosion experiences and inhibition practices in the sour gas gathering systems (2) and corrosion control considerations for the production of super sour gas wells (3) have been described in the literature. The Grizzly Valley corrosion control program used hydrogen probes, corrosion coupons, visual inspection and acoustic emission methods.

Ho-Chung-Qui (2) used pipeline inspection pig surveys, ultrasonics, radiography, well test data, flow regime analysis and metallurgical failure analysis to monitor corrosion in wet sour gas gathering systems. Teevens (3) employed the following test techniques to monitor corrosion in a super sour gas well (90% H_2S) at Panther River:

1. Immediate Response - electric resistance probe, polarization admittance instantaneous rate (PAIR) probe, hydrogen patch probe and potentiodyne probe.

2. Short-Term - double cantilever beam stress corrosion cracking (SCC) coupon, iron concentration, manganese concentration, titanium concentration, inhibitor residual levels and gas/condensate analysis.

3. Post-Mortem - visual inspection of pulled tubing, bottomhole coupons and iron-to-manganese ratios.

The potentiodyne analyzer is commonly used to determine both general and pitting corrosion rates and evaluate corrosion inhibitors under laboratory and field conditions in oil wells (4). Recently the pitfalls of this technique were discussed, and the need for other reliable monitoring methods in evaluating corrosion inhibitors used in sour service was pointed out (5). It was also suggested that electrochemical potential noise and AC impedance are promising techniques for monitoring corrosion rates and evaluating inhibitors used in sour service. These techniques were applied to both laboratory and field studies recently, and the results obtained are reported in this paper.

LABORATORY STUDIES

The performance of two commercial organic inhibitors, 9662 and 9670, was evaluated in the corrosion inhibition of carbon steel samples in a sour medium.

EXPERIMENTAL

Cylindrical mild steel samples (1 cm in diameter) of the chemical composition given in Table 1 were mounted in cured epoxy resin (Ciba Geigy Araldite BY 502 and Hardener HY951) and polished to 600 grit before immersion in the test solution. The primer (International Paint I-GP-122) was used along the perimeter of the samples to prevent crevice corrosion.

Two commercial organic inhibitors, 9662 and 9670, obtained from ESSO Chemical Canada were used together with process water obtained from ESSO Chemical Canada. The chemical analysis of the process water is given in Table 2.

The schematic of the electrochemical cell used in the studies is given in Fig. 1. The 2-L beaker cell was equipped with a gas purge and a standard reference calomel electrode placed in close proximity to the steel sample by a Luggin capillary. The mounted samples, separated by 2.5 mm, were kept in a stable parallel position by means of plastic screws.

The electrochemical AC impedance measurements were done with a commercial generator/analyzer (Solartron Model 1255) in the absence of potentiostatic control and in two-electrode configuration as described in the literature (6). The probing AC current was kept at a value which would not cause more than a 10 mV difference (peak to peak) across the cell, and at least five consecutive measurements were made at each frequency to ensure the stability of the system being investigated.

PROCEDURE

Two litres of process water were equilibrated with kerosene, and the two phases were separated. The aqueous phase was deaerated with nitrogen for 24 h and divided into two 2 L portions. One portion was saturated with hydrogen sulphide, and the other half was saturated with carbon dioxide. The two portions were combined in the cell, and a slight over-pressure of carbon dioxide was maintained (Fig. 2). The mounted steel samples were immersed in the solution, and the AC impedance and corrosion potential measurements were carried out over a period of 48 h. In experiments involving inhibitors, the concentration of the inhibitor was 250 ppm.

PIT DEPTHS

At the end of the experiments, the samples were removed from the solution and washed with distilled water. The samples were treated with a solution of rhodine to remove the corrosion products, washed with distilled water and dried. A calibrated microscope was used to measure pit

depths. The ten deepest pit depths were determined for each sample, and the average value was determined.

RESULTS AND DISCUSSION

There are two requirements for the application of electrochemical impedance spectroscopy (EIS) to monitor corrosion in practice (7). The first requirement is the optimization of the signal from the potentiostat as a function of frequency because, for low corrosion rates observed in inhibited environments, as the frequency is decreased, the current response to a constant amplitude sinusoidal voltage excitation tends to become very weak. The second requirement is to model the response in terms of circuit analogues. The usual approach taken is to curve-fit the semicircle that should result from a single-time constant capacitive response and extrapolate the low-frequency intersection of the semicircle with the real axis when the data are presented in a Nyquist format.

Recent studies (8) have shown that these two requirements can be met by working with a two-electrode configuration in the absence of potentiostatic control (9) and using a recently developed geometric analysis technique (6,7). The geometric analysis technique which determined the centres formed by three successive data points (Fig. 3) was used for analyzing the impedance diagrams obtained experimentally. The impedance measurements were further analyzed by systematic permutation of the data points involved in the projection of centres. The mathematical treatment is illustrated schematically in Fig. 4 which shows how a population of projected centres can be used in a semiquantitative evaluation of the fit made by all the data points to a simple RC model. The equivalent electrical circuit that represents simple electrochemical reaction along with the impedance diagram is shown in Fig. 5. The charge transfer resistance, also known as polarization resistance (R_P), was then evaluated from the diameter of the semicircles formed by the impedance diagrams (10). Corrosion rates were then related to the reciprocal of R_P with the Stern-Geary low-overvoltage approximation of the Butler-Volmer equation.

The Nyquist plot for process water alone is shown in Fig. 6 which gave a maximum of 13 kΩ. Similar plots for process water containing 250 ppm of inhibitors 9662 and 9670 are given in Fig. 7, and maxima of 30 kΩ and 38 kΩ were observed for 9662 and 9670 inhibitors, respectively, showing 9670 to be slightly superior to 9662 in corrosion inhibition.

Polarization resistance was monitored for process water alone, process water containing inhibitors 9662 and 9670 over 48 h, and the data are presented in Fig. 8. The polarization resistance for process water stayed relatively constant after rising from 10 kΩ to about 30 kΩ. On the other hand, the polarization resistance values for process water containing added inhibitor gave fluctuating values in a sinusoidal fashion. Up to 20 h, the polarization resistance

due to added 9670 inhibitor is higher than 9662, and this pattern reversed between the interval of 25-30 h. At 35 h, 9670 appears to perform better than 9662 which is reversed at 50 h.

The polarization resistance for the first 15 h is depicted in Fig. 9. In the initial stages 9662 gave higher values than 9670, and this trend reversed after 10 h. These data show that both 9662 and 9670 are equally effective in corrosion inhibition as far as general corrosion is concerned.

The magnitude of the angle of depression formed between the abscissa and the the projected arc centre has been found to indicate the degree of pitting corrosion and correlated well with the experimentally measured pit depths (11). The experimental data on the sum of depression angles over 48 h are plotted against time in Fig. 10. The sum of the depression angle is greater in the system containing 9662 than the system containing 9670 indicating pitting corrosion is greater in the system with 9662 than the system containing 9670. The measured pit depths are plotted against the depression angle in Fig. 11. The scatter of the points is quite large although a linear trend is noticeable. The average of ten deepest pits gave 9.75 and 8.1 μ in case of systems containing 9662 and 9670 inhibitors, respectively. These data show that pitting in the case of the system containing 9662 is slightly higher than in the system containing 9670.

CONCLUSIONS

Polarization resistance values obtained from AC impedance measurements showed the two corrosion inhibitors, 9662 and 9670, to be equally effective in inhibition of general corrosion in sour media.

The data on depression angles and microscopically measured pit depths correlated reasonably well and showed that the sample in inhibitor 9662 experienced a slightly greater degree of pitting than the sample in inhibitor 9670.

FIELD STUDIES

Field evaluation of the performance of inhibitors was carried out at Wimborne, Alberta. Commercial cylindrical mild steel electrodes (3 cm long and 3 mm diameter) were screwed onto a linear polarization resistance probe and the probe screwed into the pipe. The experimental arrangement of the electrochemical probe fitted into the pipe is shown in Fig. 12.

The AC impedance analyzer, together with an HP computer model 86 and associated screen and printer, were placed in a trailer as shown in Fig. 13. The AC impedance measurements were done with the commercial generator/analyzer (Solartron Model 1250) in the absence of potentiostatic control and in a two-electrode configuration. The probing AC current was kept at a value which would not cause more than 10 mV difference (peak to peak) across the cell, and at

least five consecutive measurements were made at each frequency to ensure the stability of the system being studied.

Two commercial inhibitors, 9662 and 9670 represented as A and B, respectively, obtained from ESSO Chemical Canada were used. The analysis of process water is given in Table 3.

The field conditions data are given in Table 4.

PROCEDURE

After connecting the probe in the pipe through an electrical barrier to the AC impedance analyzer (Solartron Model 1250), the impedance measurements were done once a day for ten days for every run. The first run was done without any inhibitor. The second and third runs were done with the addition of inhibitors 9662(A) and 9670(B), respectively. Each run lasted for ten days.

PIT DEPTHS

Pit depths on the samples were measured by Mitutoyo Contact Tracing and Hyscan Corrosion Analysis System (Hymark Ltd., Ottawa). In the laser method, Helium Neon Laser beam emitted from the aperture window of the unit scans across the surface of the corroded sample. By digitizing the X Y Z components of a grid of points on the surface, it is able to detect and locate pits and peaks. The value of the pit depth and peak height are calculated with reference to an imaginary plane established by the operator by choosing up to 20 high points on the surface. The maximum pit depth, the mean pit depth and the volume loss of material are used as criteria for corrosion interpretation. All the flat coupons and rod samples were analyzed by these methods.

The pit depths on the AC impedance electrode samples were measured by means of a calibrated metallurgical microscope. The ten deepest pits on each electrode were measured, and the average pit depth was calculated.

RESULTS AND DISCUSSION

The AC impedance data in the form of Nyquist plots are presented in Figs. 14 to 16. Figures 14 to 16 represent process water, process water with inhibitor 9662 and process water containing inhibitor 9670, respectively. The polarization resistance value is low for process water (350 Ω) and high values in the case of process water with added inhibitors 9662 (80 kΩ) and 9670 (60 kΩ). These values show that both 9662 and 9670 inhibitors are effective with 9662 proving to be somewhat superior to 9670. The polarization resistance data as a function of time are plotted in Fig. 17. The polarization resistance data give high values for the systems containing the inhibitors as opposed to systems without added inhibitor. It is also obvious that the inhibitor 9662 (A) is slightly superior to 9670 (B).

The data on the sum of depression angles of the Nyquist plots from the real axis over a period of ten days for all the three runs representing process water, process water with inhibitor 9662 and inhibitor 9670 are given in Table 5. The sum of depression angles with the system containing inhibitor 9662 is slightly higher than process water alone while the value for inhibitor 9670 system is significantly higher. In earlier studies, it was shown that the value of depression angle is related to the degree of pitting. The higher the depression angle, the greater the extent of pitting. From the data in Table 5, it appears that the system containing inhibitor 9670 is undergoing a higher degree of pitting than the system containing inhibitor 9662. The microscopically measured pit depths on the samples are plotted against the depression angle in Fig. 18, and the linear plots are good. This supports the relationship between the depression angle and pitting corrosion.

The data on pit depths obtained by the Mitutoyo contracer on both rod coupons and flat coupons under uninhibited and inhibited conditions are summarized in Tables 6a and 6b, respectively. The average pit depth ranged from 0.077 to 1.10 mm for flat coupons under uninhibited conditions, and the deepest pit depth gave a range of 0.17 to 2.06 mm. In the case of the rod samples, the average pit depths were 0.067 and 0.094 mm, and the corresponding values for deepest pits were 0.15 and 0.29 mm, respectively. In the case of the system containing inhibitor 9662, the flat coupons gave 0.005 mm to <0.005 mm pit depths, and the rod sample a value of 0.01 mm (Table 6b). With inhibitor 9670, the pit depths for flat coupons were in the range of 0.005 to 0.02 mm, and the rod samples had values ranging from 0.005 to 0.025 mm.

Using the deepest pit and average pit depth data on both flat coupons and rod samples, the per cent inhibition was calculated, and the resulting values are given in Table 7. The values of per cent inhibition calculated based on deepest pit depths are higher than the values calculated on the basis of average pit depths. With the exception of sample ES 187, all of the data on per cent inhibition show the inhibited system containing inhibitor 9662 to be slightly superior to inhibited 9670 system in inhibiting the degree of pitting. The pit depth tracings obtained with flat coupons X757, X765 and 4 are given in Fig. 19. Similar tracings for rod samples ES 226, 184 and 181 are given in Fig. 20. It is obvious from these figures that the degree of pitting is of the order X757 < X765 < 4 and ES 227 > 184 > 181. Again it supports the view that inhibited system 9662 is marginally superior to the inhibited 9670 system.

Figures 21 and 22 show photographs of the three flat samples and the three rod samples, respectively. These figures also show the differences and the degree of pitting of the samples. In Fig. 23, the photomicrographs of the flat samples uninhibited, and inhibited with 9670 and 9662 inhibitors are given. The uninhibited sample showed cracks and numerous pits on the surface. The sample inhibited with 9670 showed some discrete pits while the sample inhibited with inhibitor 9662 showed hardly any pitting.

Pit depth data obtained by laser beam scanner on flat coupons and rod samples exposed to process water, process water containing 9662 inhibitor and process water containing 9670 inhibitor are summarized in Tables 8a and 8b. Based on the pit depth values, the per cent inhibition was calculated. These data also show that inhibitor 9662 is slightly superior to 9670 in inhibition of pitting corrosion. Line profiles of the flat coupons X757, X765 and 4, and rod samples 227, 184 and 181 are shown in Fig. 24 and 25, respectively. These figures show the degree of pitting to be in the order X757 < X765 < 4 for the flat coupons and 227 > 184 > 181. These data are consistent with the data obtained by contracer and microscope.

CONCLUSIONS

The polarization resistance data obtained from AC impedance measurements showed both 9662 and 9670 were effective inhibitors, with 9662 showing marginally superior performance to 9670.

The sum of depression angles correlated fairly well with the microscopically measured pit depths on the electrode. The degree of pitting appears to be slightly higher on samples exposed to 9670 inhibitor than those exposed to 9662 inhibitor.

Pit depth measurements on samples by contracer and laser beam methods showed good agreement, and lead to the conclusion that inhibitor 9662 is slightly superior to 9670 in inhibition of the degree of pitting.

ACKNOWLEDGEMENTS

We wish to thank ESSO Chemical Canada staff for providing help in the field studies.

REFERENCES

1. Lawson, V.B., Duncan, C. and Treseder, R.S. Corrosion '87, Paper No. 52, National Association of Corrosion Engineers; Houston, TX; 1987.

2. Ho-Chung-Qui, D.F. and Williamson, A.I. Corrosion '87, Paper No. 46, National Association of Corrosion Engineers; Houston, TX; 1987.

3. Teevens, P.J. Corrosion '87, Paper No. 47, National Association of Corrosion Engineers; Houston, TX; 1987.

4. Martin, R.L. Corrosion '77, Paper No. 140, National Association of Corrosion Engineers; Houston, TX; 1977.

5. Sastri, V.S.CANMET, Report MTL 88-62(J); Bulletin of Electrochemistry, 000; 1991.

6. Roberge, P.R., Halliop, E., Asplund, M. and Sastri, V.S. J. Appl. Electrochem. 20:1004; 1990.

7. Roberge, P.R. and Beaudoin, R. J. Appl. Electrochem 18:601; 1988.

8. Roberge, P.R. and Beaudoin, R. J. Appl. Electrochem 18:38; 1988.

9. Silverman, D.C. and Carrico, J.E. Corrosion 44:280; 1988.

10. Hladky, K., Callow, L.M. and Dawson, J.L. Br. Corr. J. 15:20; 1980.

11. Roberge, P.R., Sastri, V.S., Halliop, E. and Asplund, M. Corr. Sci. (in press).

Table 1. Chemical composition of the steel (wt %).

C	Si	Mn	S	P	Cr	Ni	Cu	B	Sn
0.065	0.0076	1.10	0.28	0.084	0.029	0.013	0.014	0.0008	0.0031

Table 2. Composition of process water.

Species	Concentration (mg/L)
Calcium	21 500
Magnesium	2 120
Sodium	59 900
Potassium	4 720
Chloride	152 000
Sulphate	118
Total alkalinity as $CaCO_3$	618
pH	7.24
Carbonate	<0.5
Bicarbonate	754
Total filterable residue	244 400

Table 3. Field process water analysis.

Species	Concentration (mg/L)
Sodium	52 190
Potassium	6 447
Calcium	21 880
Magnesium	2 922
Chloride	132 762
Bicarbonate	859
Sulphate	388
Total solids	217 448
pH	7.24

Table 4. Field conditions.

H_2S	14%
CO_2	1.2%
Flow rate	210 m^3/day brine; 43 m^3/day of condensate
Oil (condensate):Water ratio	0.17
Chemical inhibitor dosage	Desired - 120 ppm (based on brine) Actual - varied from 35 to 260 ppm

Table 5. Sum of depression angles.

Days	No inhibitor	9662 (A)	9670 (B)
1	22.8	30.2	36.3
2	48.7	60.6	72.6
3	77.2	85.7	108.9
4	99.7	109.4	145.2
5	114.1	128.4	181.5
6	136.1	152.1	210.0
7	155.3	175.8	249.3
8	177.3	199.5	286.5
9	199.3	223.2	321.3
10	221.3	245.8	354.5

Table 6a. Pit depths (mm) on uninhibited samples.

	Flat coupons			
	1	2	3	4
	0.020	0.110	1.20	2.06
	0.045	0.170	0.32	1.60
	0.060	0.045	1.66	1.20
	0.060	0.110	0.36	1.12
	0.040	0.050	0.90	0.48
	0.070	0.040	0.26	0.12
	0.065	0.050	1.00	
	0.050	0.090		
	0.320	0.150		
		0.090		
Average	0.077	0.0905	0.81	1.10
Deepest pit	0.32	0.17	1.66	2.06

	Rod coupons	
	ES 227	ES 228
	0.030	0.120
	0.040	0.020
	0.060	0.030
	0.050	0.050
	0.100	0.060
	0.150	0.210
	0.090	0.080
	0.070	0.060
	0.080	0.050
	0.095	0.060
		0.290
Average	0.067	0.094
Deepest pit	0.150	0.290

Table 6b. Pit depths (mm) on inhibited samples.

Flat coupons	Inhibitor 9662
X755	0.005
X757	0.005
X758	<0.005
Rod coupons	
ES 181	0.010
Flat coupons	Inhibitor 9670
X769	0.005
X768	0.005
X766	0.005
X765	0.02, 0.01, 0.01 (average 0.013)
Rod coupons	
ES 187	0.005
ES 184	0.020, 0.020, 0.010, 0.025
	0.015, 0.020, 0.015, 0.015 (average 0.0175)

Table 7. Data on per cent inhibition calculated from pit depths.

	Per cent inhibition			
	Inhibitor 9662		Inhibitor 9670	
Sample	Average pit depth	Deepest pit	Average pit depth	Deepest pit
Flat coupon 1	94.7	97.1	86.3	88.2
Flat coupon 2	93.5	98.4	83.2	93.7
Flat coupon 3	99.4	99.7	98.4	98.8
Flat coupon 4	99.5	99.8	98.8	99.0
Rod coupon ES 181	85.1	93.3		
	89.4	96.5		
Rod coupon ES 187			92.5	96.7
			94.7	98.3
Rod coupon ES 184			74.0	83.3
			81.4	91.4

Table 8a. Pit depth (mm) data by laser profilometer (flat coupons).

Sample	Pit depth (mm)		Inhibitor	Per cent inhibition
	Maximum	Average		
1	2.186	0.114	None	
2	1.962	0.074		
2	3.114	0.518		
3	3.059	0.476		
4	1.885	0.274		
X758	0.374	0.020	9662	90.8
X757	0.123	0.032		
X755	0.177	0.026		
X769	0.177	0.014	9670	85.5
X768	0.355	0.020		
X766	0.473	0.023		
X765	0.415	0.030		

Table 8b. Pit depth (mm) data by laser profilometer (rod coupons).

Sample	Pit depth (mm)		Inhibitor	Per cent inhibition
	Maximum	Average		
ES 228*	0.240	0.062	None	
ES 228**	1.042	0.102	None	
ES 227*	0.376	0.054	None	
ES 227*	1.494	0.055	None	
ES 227**	0.400	0.051	None	
ES 181*	0.101	0.011	9662	80.3
ES 181**	0.349	0.048		
ES 184*	0.103	0.017	9670	77.1
ES 184**	0.304	0.031		
ES 187*	0.111	0.023		
ES 187**	0.643	0.060		

* right side
** left side

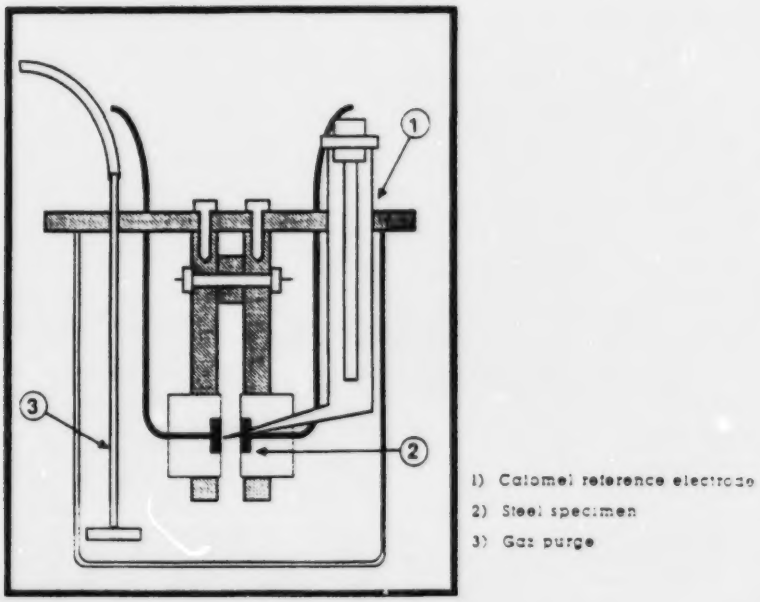


Fig. 1. Electrochemical cell.

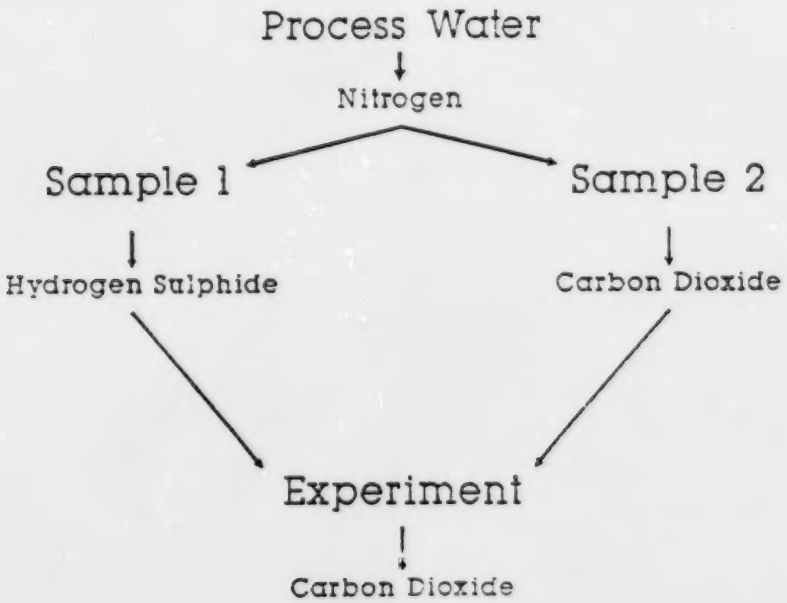


Fig. 2. Procedure used in electrochemical experiments.

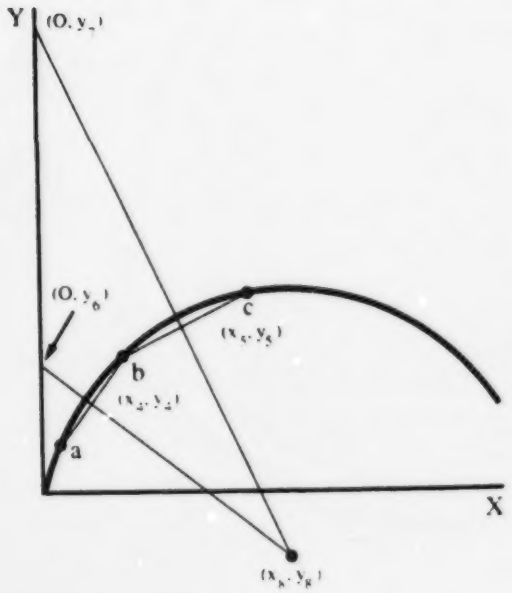


Fig. 3. Illustration of geometric technique.

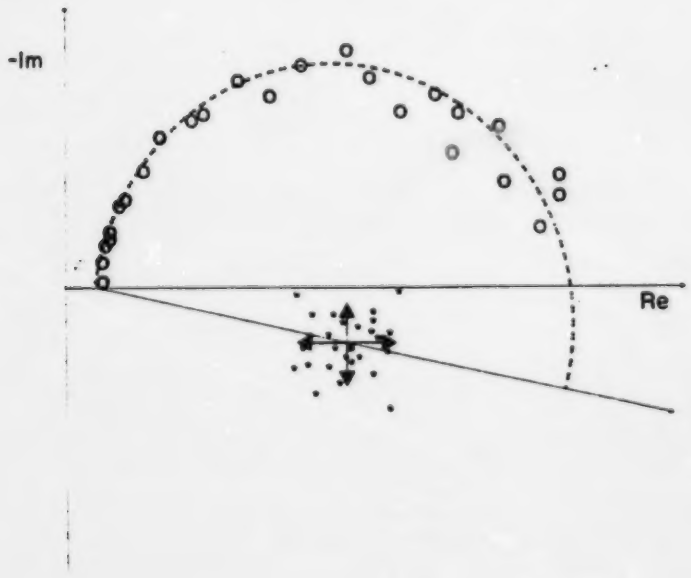


Fig. 4. Projection of centres of arcs.

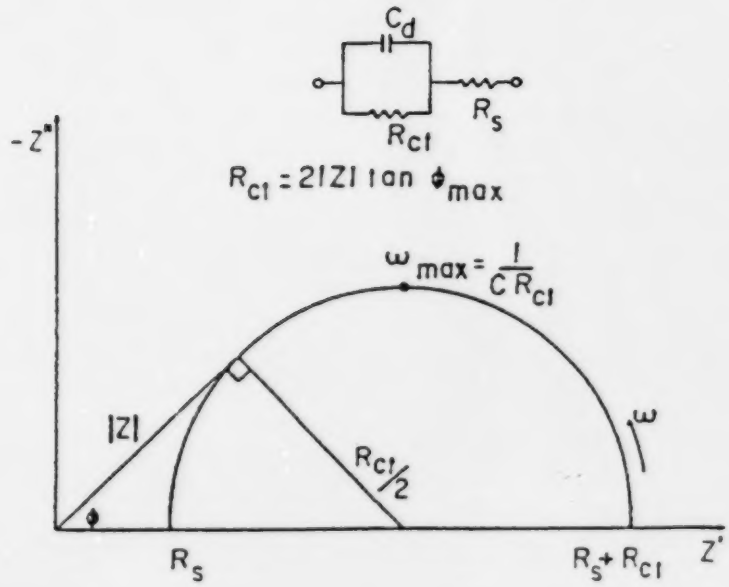


Fig. 5. Nyquist plot and RC circuit.

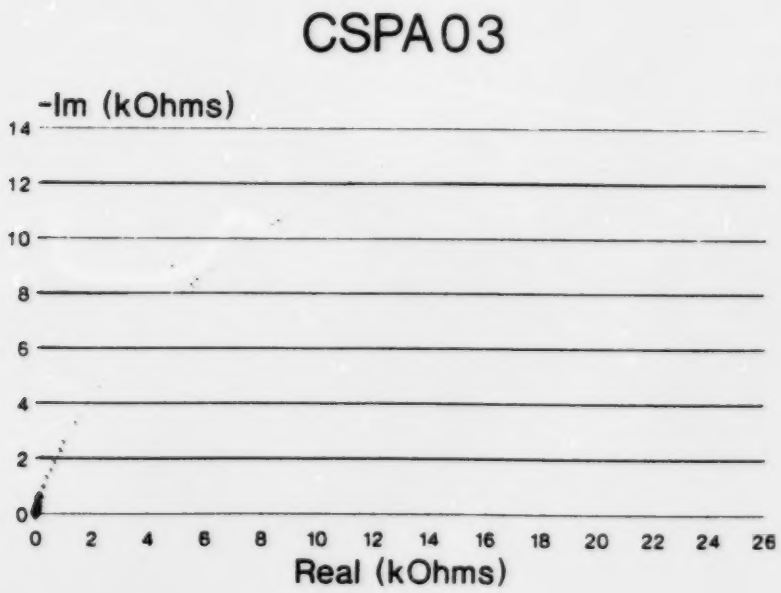


Fig. 6. Nyquist plot for process water.

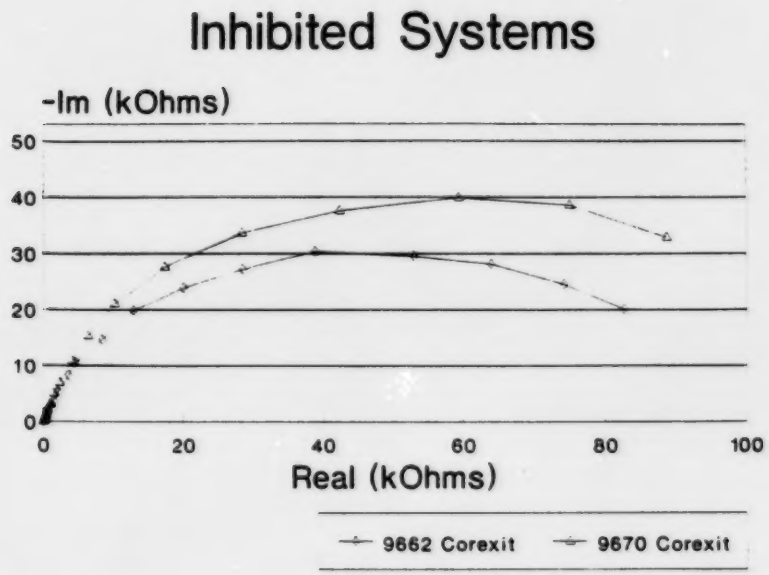


Fig. 7. Nyquist plots with inhibitors.

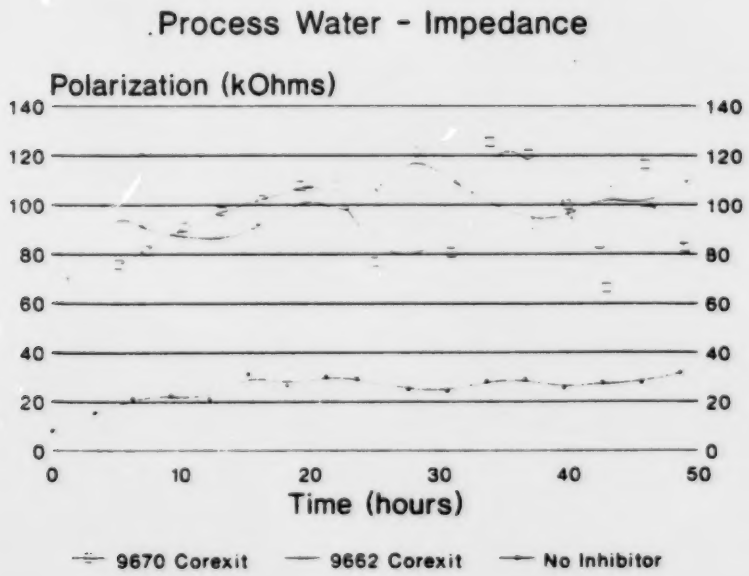


Fig. 8. Plot of polarization resistance vs time for 48 h.

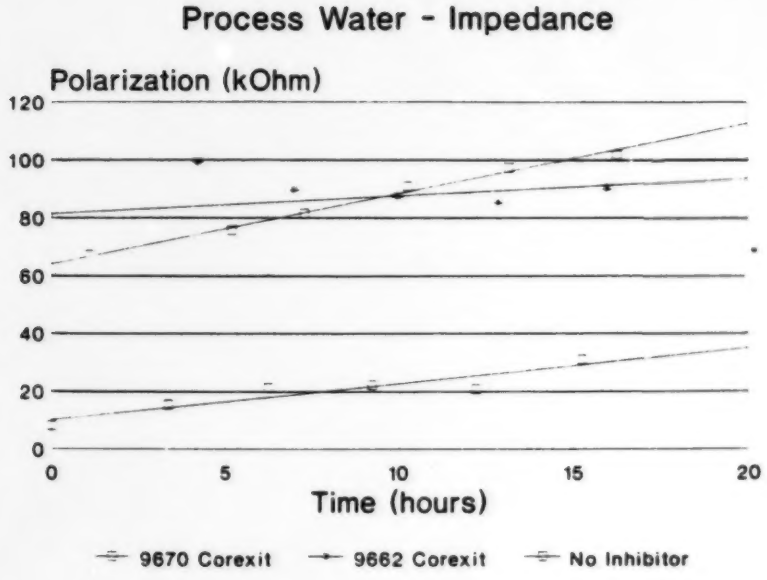


Fig. 9. Plot of polarization resistance vs time for 15 h.

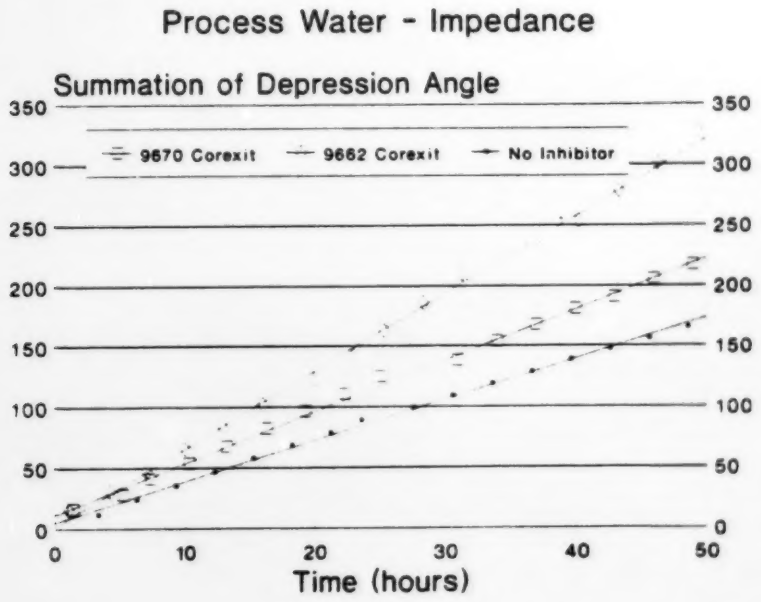


Fig. 10. Plot of sum of depression angles vs time.

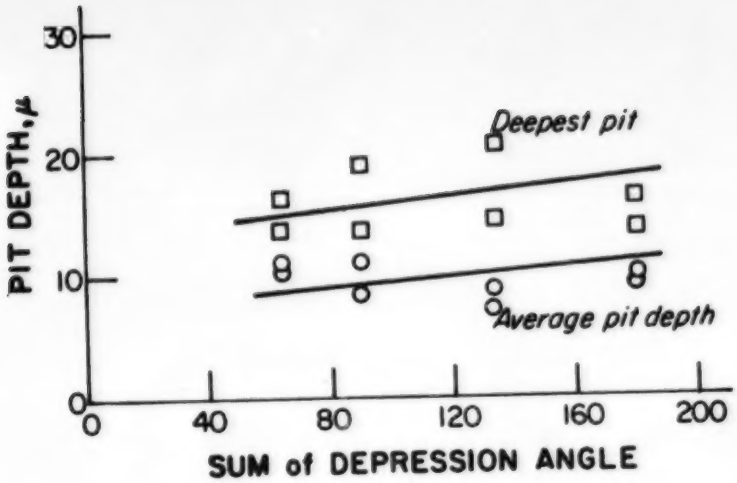


Fig. 11. Plot of average and deepest pit depth vs sum of depression angle.

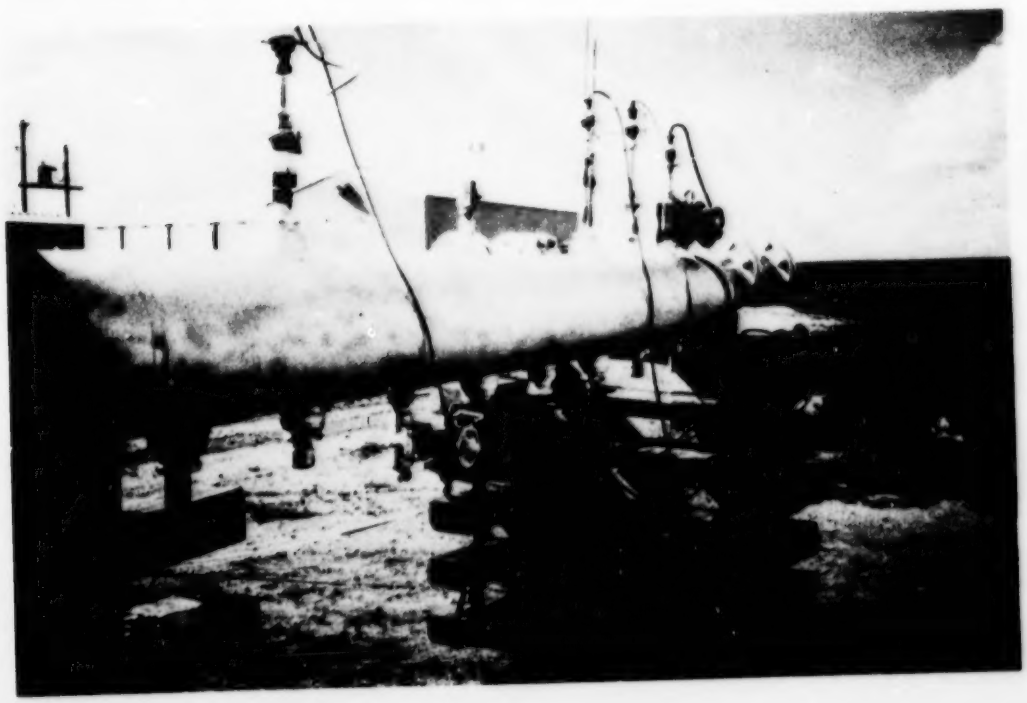


Fig. 12. Pipe with assembled electrochemical probes.

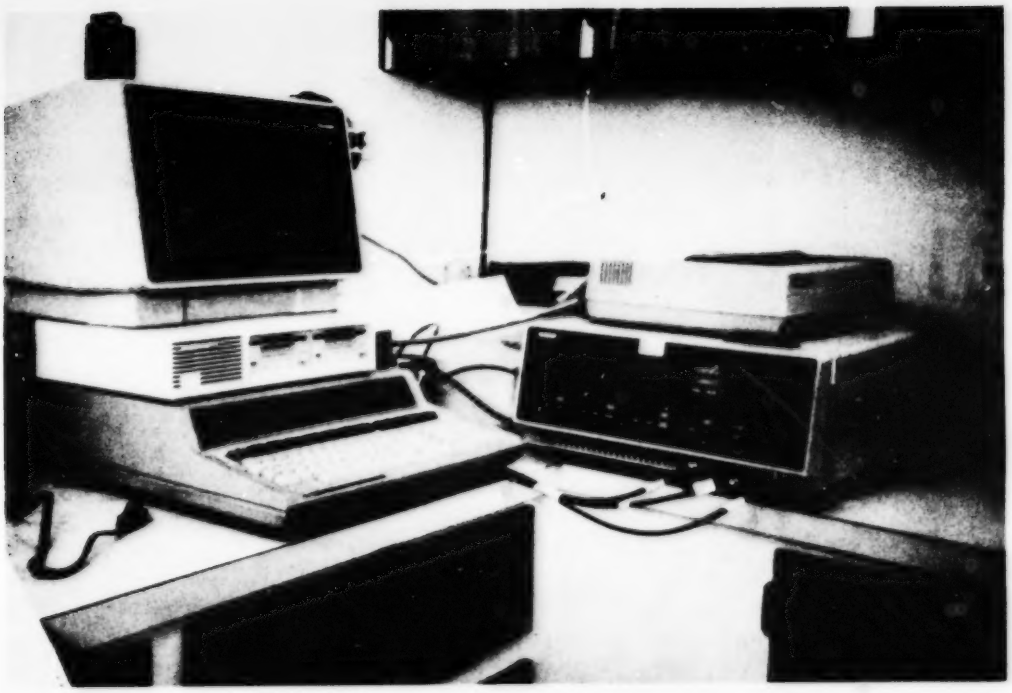


Fig. 13. AC impedance analyzer.

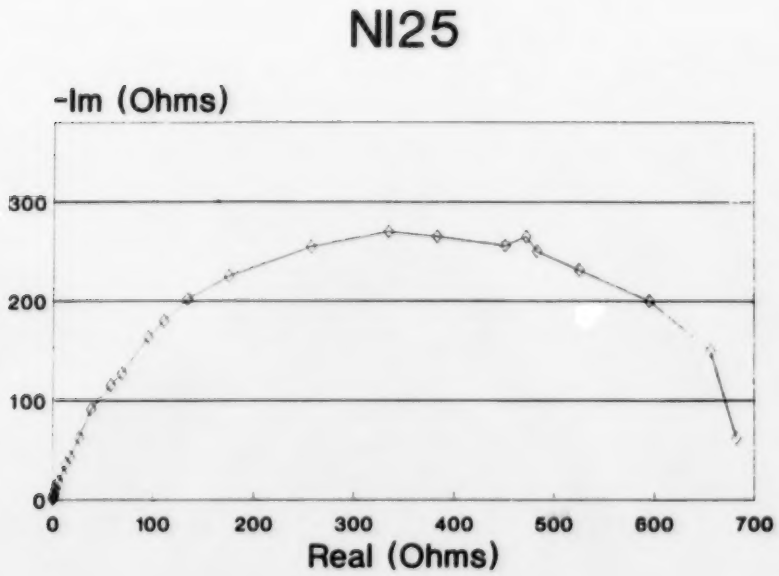


Fig. 14. Nyquist plot for process water.

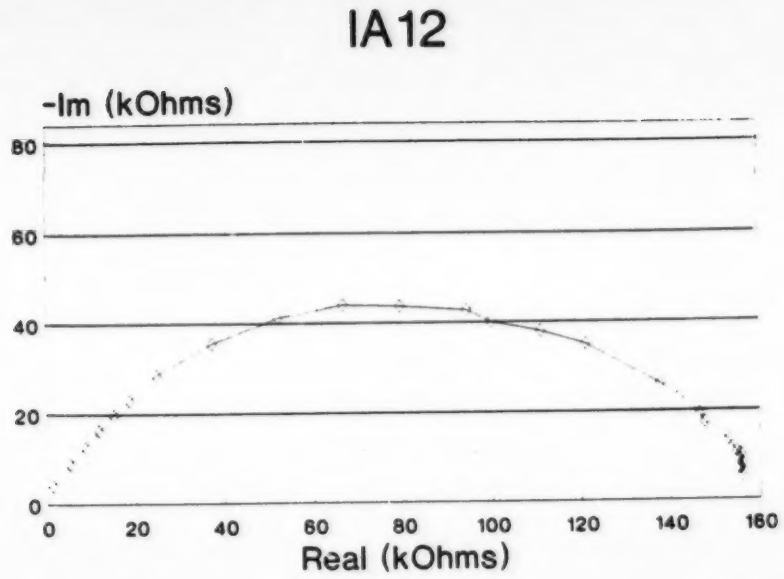


Fig. 15. Nyquist plot for system with inhibitor 9662.

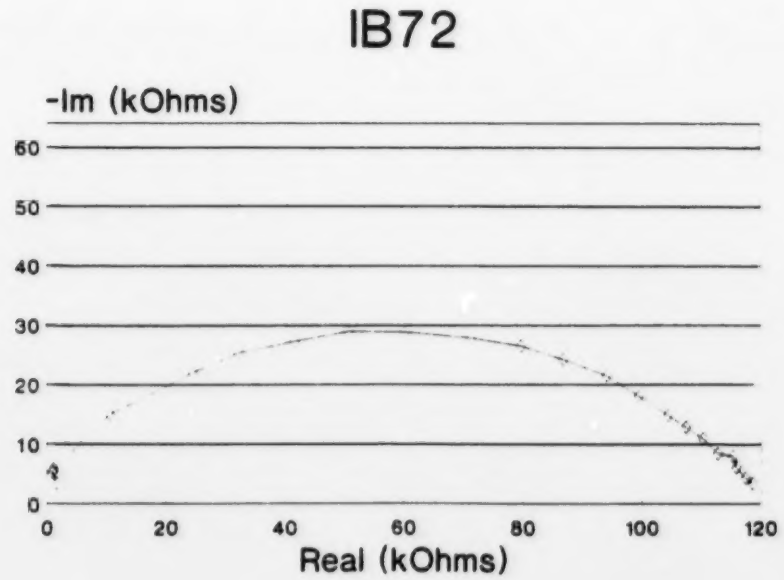


Fig. 16. Nyquist plot for system with inhibitor 9670.

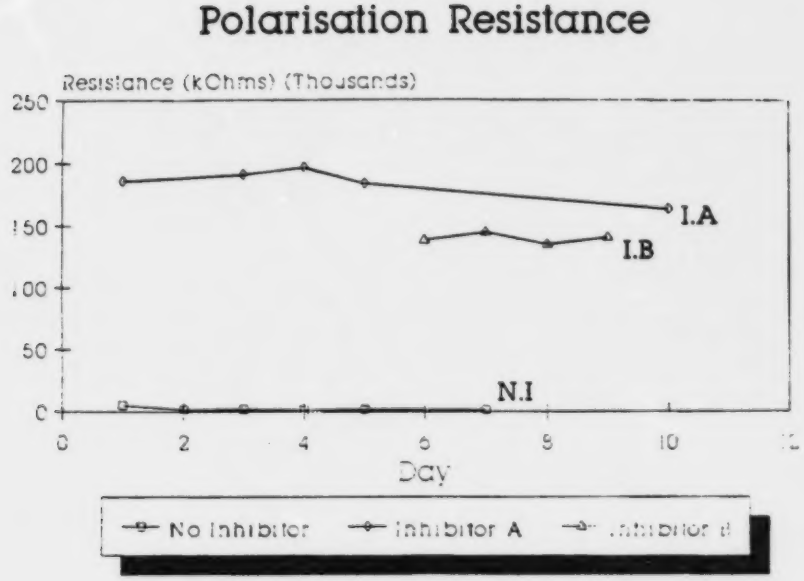


Fig. 17. Polarization resistance vs time for field tests.

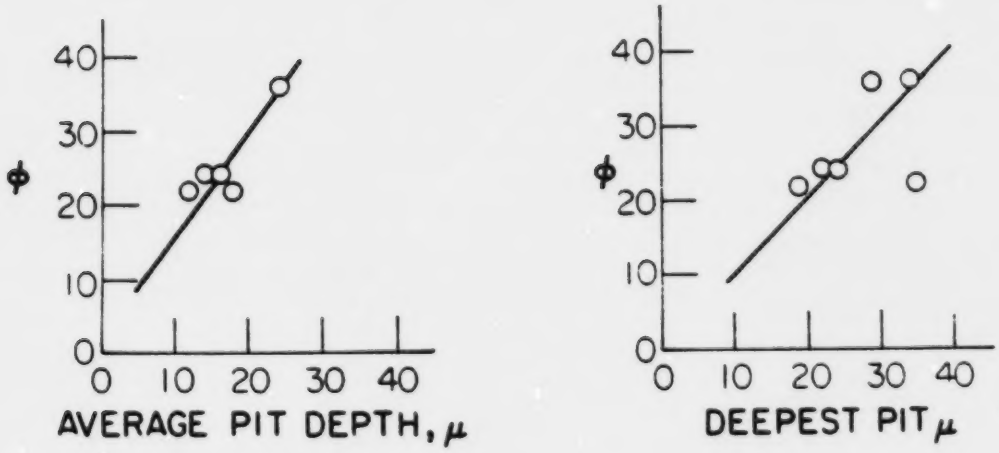


Fig. 18. Plot of pit depths vs depression angle.

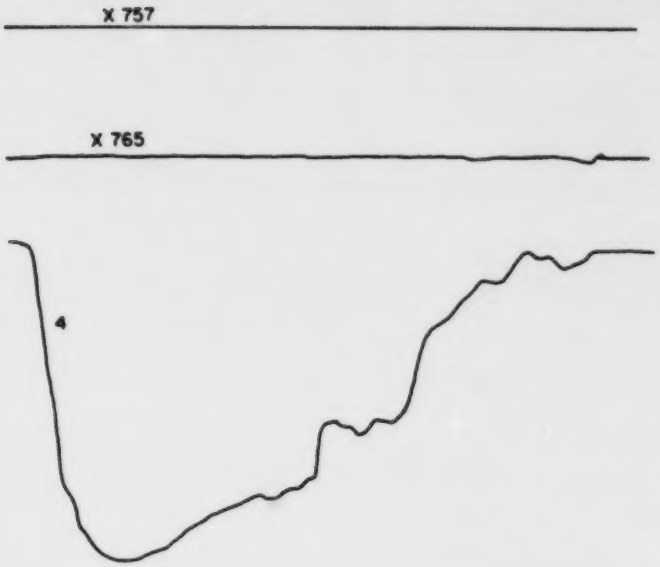


Fig. 19. Profilometer trace of flat coupons.

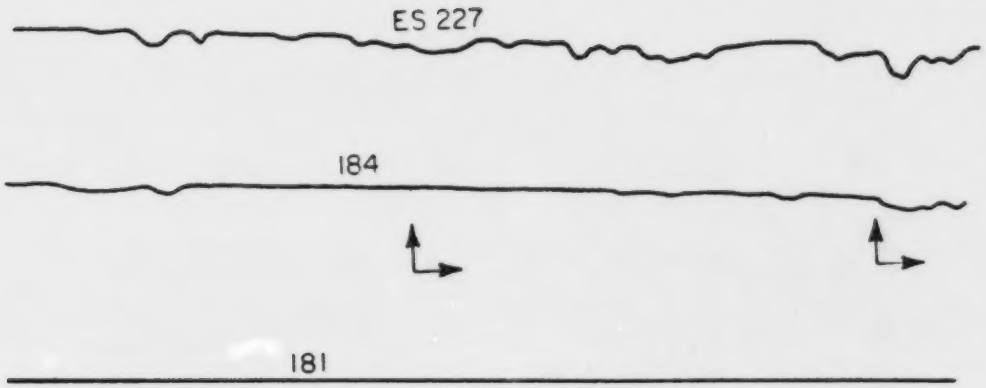


Fig. 20. Profilometer trace of rod samples.

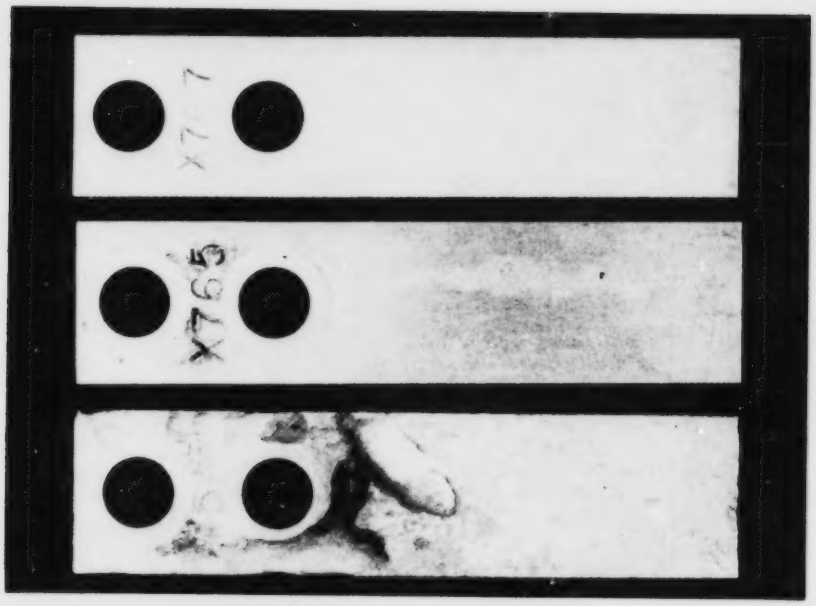


Fig. 21. Photograph of the three flat coupons.

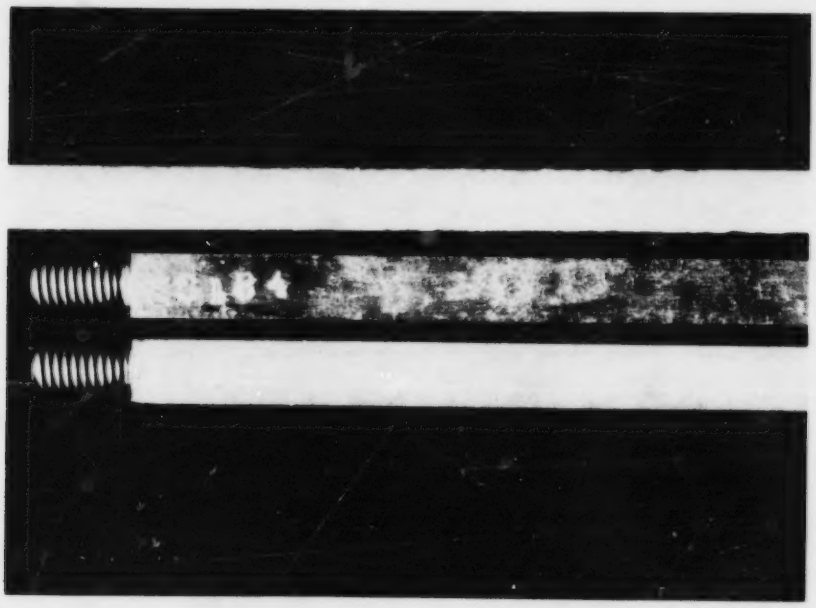
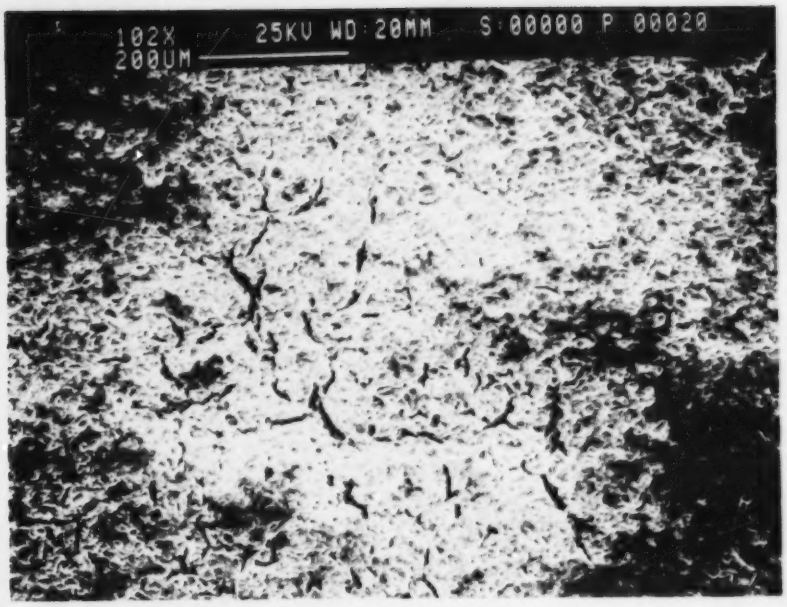
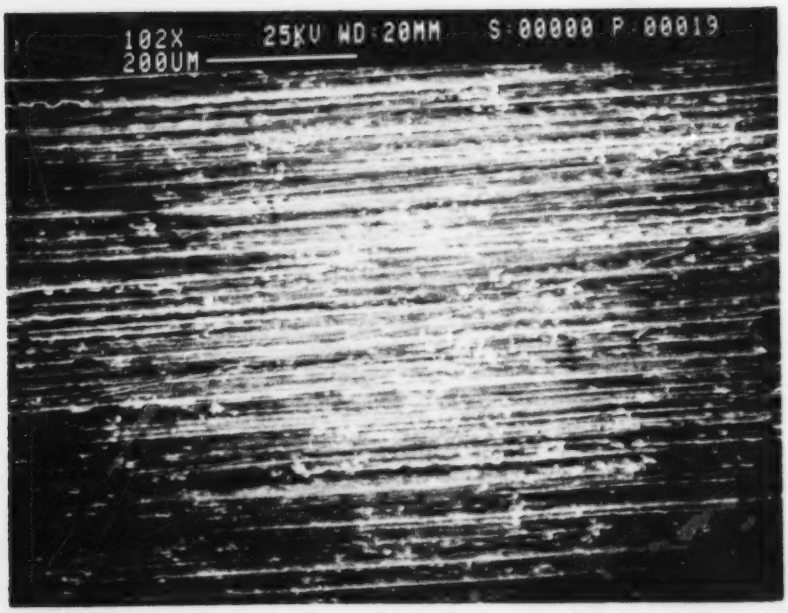


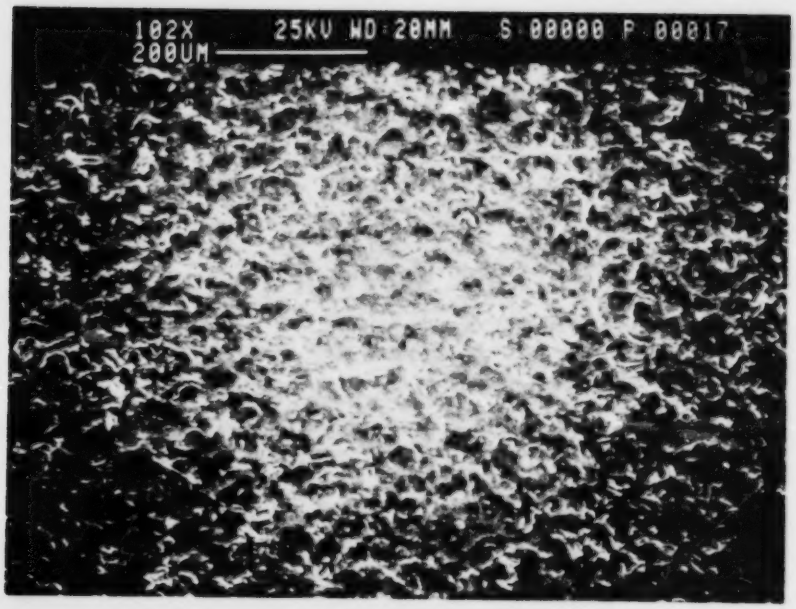
Fig. 22. Photograph of the three rod samples.



(a) uninhibited



(b) X768 inhibited with 9670



(c) X757 inhibited with 9662.

Fig. 23. Photomicrographs of flat coupons

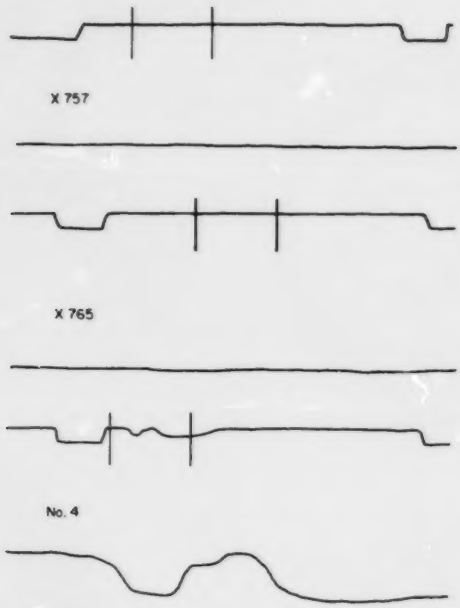


Fig. 24. Line scan obtained by laser beam of flat coupons.

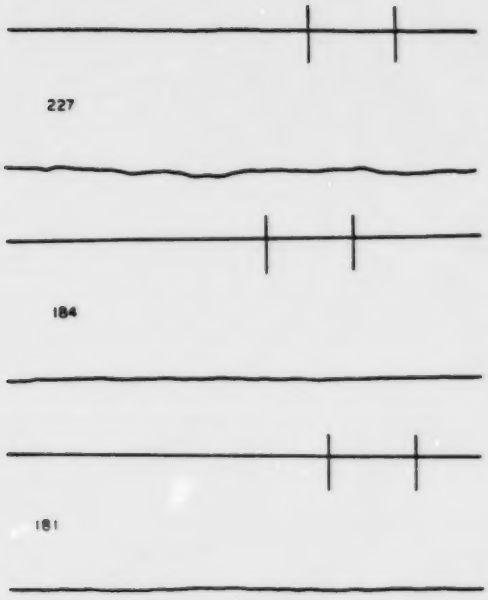


Fig. 25. Line scan obtained by laser beam of rod samples.